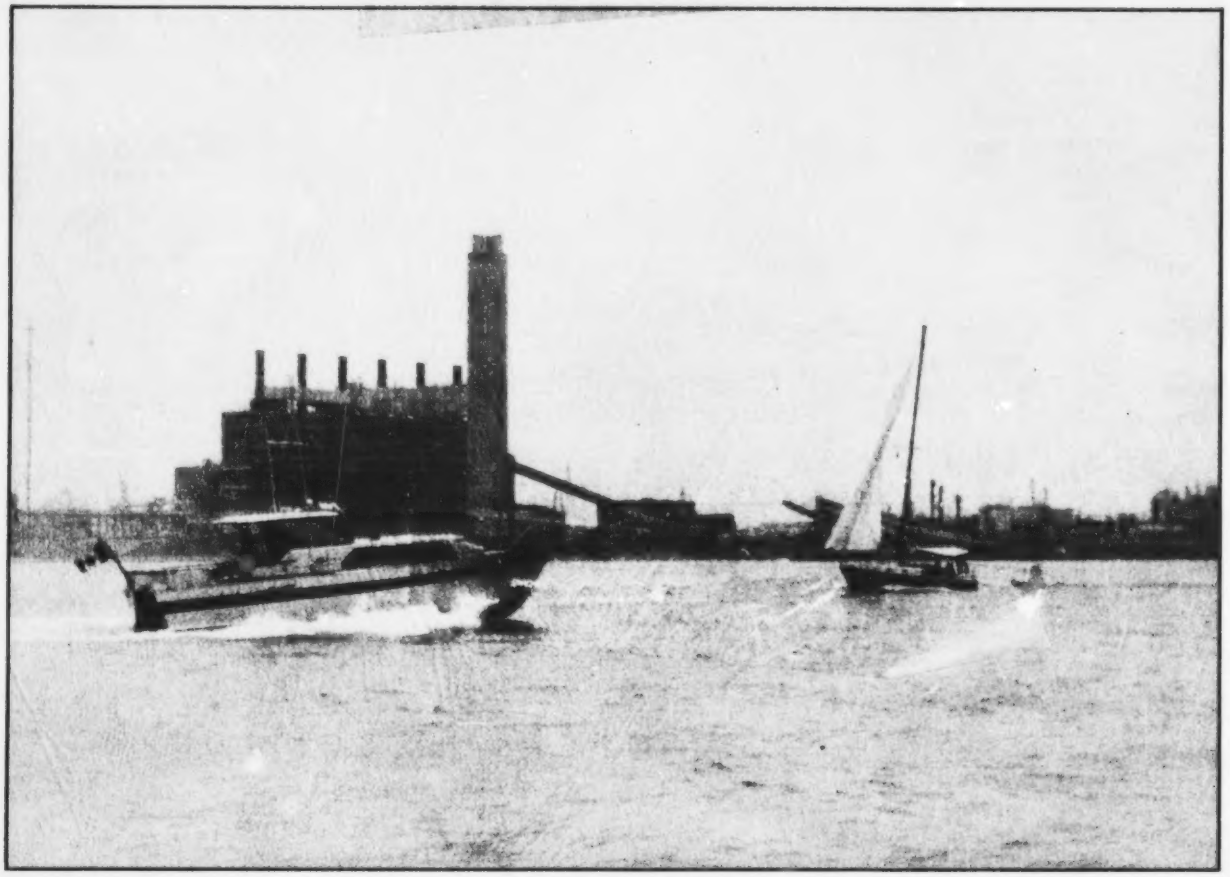
ST. CLAIR RIVER ORGANICS STUDY

WASTE DISPERSION



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WASTE DISPERSION

IN THE ST. CLAIR RIVER

by

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Ontario Ministry of the Environment
Water Resources Branch
Great Lakes Unit
November 1979

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FOREWORD

Investigation of organic chemicals in industrial effluents along the St. Clair River commenced in 1975 after the adoption of gas chromatography - mass spectrometry analytical methodologies by the Laboratory Services Branch of the Ministry of the Environment made the detection of low concentrations of such compounds possible. In a preliminary report, 'Organic Compounds of Industrial Origin in the St. Clair River', developed as an internal working document in January of 1977, positive identification was made of some 47 organic compounds discharged to the St. Clair River.

The St. Clair River Organics Study Group was formed early in 1977 in response to concerns about the presence and significance of the organic compounds identified, particularly in relation to possible effects on public water supplies downstream and the potential bio-accummulation of such compounds by fish resident in or frequenting this important waterway. Also, it was felt that a comprehensive assessment of water quality conditions and aquatic life was warranted to permit a comparison with unpublished biological data collected in 1968.

Representation on the Study Group included staff from various branches of the Ministry of the Environment and the Special Studies and Services Branch of the Ministry of Labour. Early in its deliberations, the Study Group identified the following goal:

> TO ASSESS THE PRESENCE AND SIGNIFICANCE OF ORGANIC CHEMICAL COMPOUNDS IN THE ST. CLAIR RIVER SYSTEM AND TO ESTABLISH FROM THIS PROGRAMME RECOMMENDATIONS FOR CONTROL MEASURES AND FURTHER STUDIES THAT MAY BE REQUIRED IN RELATION TO HUMAN HEALTH AND ENVIRONMENTAL EFFECTS.

In order to accomplish the above goal, the following ten objectives were identified:

1. Identification and quantification of organic compounds in industrial discharges, St. Clair River water, potable water supplies, bottom sediments and fish.

2. Completion of a literature search on the characteristics and effects of the organic compounds identified. Lethal, sub-lethal and synergistic effects of these compounds on human and aquatic life to be considered.

3. Determination of the significance of chlorinating trace amounts of these organic materials in industrial cooling water discharges, sewage plant effluents and in potable water supplies.

4. Determination of the types and concentrations of compounds causing fish toxicity and fish tainting problems.

5. Estimation of the dissolved organics concentration at any point in the river based on effluent quality and flow measurements.

6. Completion of benthic macroinvertebrate, aquatic plant, sediment and water quality studies on the river in terms of biological and common chemical indicators. Results to be compared to survey work carried out in 1968-69. Assessments of mercury levels in sediments to be completed.

7. Determination of the potential carcinogenicity of organic compounds through quick-screening microbiological tests for mutagenesis.

8. Establishment of whether biodegradation or alteration of organic compounds occurs through bacterial action in sediments.

9. Development of recommendations clarifying levels to which contaminants must be reduced, as a basis for necessary treatment and effluent controls.

10. Clarification of the need for additional research to establish potential dangers to human health or the natural environment where this information is lacking.

Work on the component studies related to these objectives progressed throughout 1977 and 1978 and into 1979. As a result of these efforts the following reports will be published during 1979, to form an integrated series covering the objectives defined previously.

(1) Identification and Quantification of Organic Compounds.
(2) Fish Toxicity and Tainting Evaluations for Selected Industrial Effluents.
(3) Waste Dispersion.
(4) Biological Surveys 1968 and 1977.
(5) The Detection of Mutagenic Activity; Screening of Twenty-three Compounds of Industrial Origin.
(6) Biodegradation of Organic Compounds.

Wherever possible, each of these reports will present conclusions and advance recommendations to achieve an improvement of water quality in the St. Clair River system or to clarify additional research requirements in regard to potential human health or environmental effects.

SUMMARY OF FINDINGS

This study has successfully adapted an existing mathematical dispersion model to the prediction of in-stream concentrations of conservative substances from shore-based discharges to the St. Clair River. The non-dimensional dispersion coefficient which is a necessary input to such models was investigated in the field and found to be much higher than the classical values normally used in dispersion predictions.

Predictions of the fate of non-conservative pollutants can also be made by incorporating an estimate of the decay rate of the pollutant into the model. Research remains to be carried out, however, in determining appropriate decay coefficients for the local situation. Nevertheless, we are now better able to determine the effluent loading and concentration restrictions necessary to ensure the achievement of water quality objectives and the protection of downstream water use.

INTRODUCTION

The St. Clair River, like the other connecting waterways of the Great Lakes, is the recipient of treated effluents from intensive urban and industrial development. In spite of the large volumes of water carried by these rivers, the necessity for shore-based discharges (in order to keep navigation channels free of obstructions) means that only a small portion of the river flow is available for waste dispersal.

This study of dispersion characteristics in the St. Clair River is intended to provide the basis for determining the appropriate effluent requirements associated with protecting downstream water uses. An assessment is made of the importance of initial dilution and lateral mixing factors.

BACKGROUND

Knowledge of the lateral dispersion coefficient (E_z) is a key to the determination of mixing characteristics of open channels and a valuable input in pollution control analysis especially those involving mathematical modelling.

During the late 1960's many investigators attempted to predict values for the lateral dispersion coefficient using the theory of diffusion by continuous movement as developed by Taylor (1921). Elder (1959) used Taylor's analysis coupled with the Reynolds analogy to estimate both longitudinal and lateral dispersion coefficients.

Subsequent to the findings of these classical investigations, Fischer (1966), Glover (1964), Sayre and Chang (1968), Yotsukura et al (1970) and others carried out field and laboratory studies to investigate lateral mixing based on the experimental as well as theoretical formula derived by Elder:

$$E_z = k\, U_\star\, H;$$

where k is a constant called the non-dimensional dispersion coefficient;

$U_\star$ is the shear velocity; and

H is the average depth of water flow.

Okoye (1970) summarized a large amount of data on the non-dimensional dispersion coefficient derived from laboratory and field studies. These are documented in Appendix A.

An estimate of the variance of concentration distribution is normally used in describing the dispersion mechanism in open channel flow. In this study, however, the method of moments was applied to

the distribution of concentration flux (mass transported per unit time) so as to account for the effect of net transverse velocities by including the variation in depth and velocity distribution; after Fischer (1967) and Holley et al (1972). The variance of concentration flux distribution (σ^2) is estimated by:

$$\sigma^2 = \frac{\sum_{o}^{B} cuhz^2 \Delta z}{\sum_{o}^{B} cuh \Delta z}$$

where c, u, h are local values of concentration, velocity, and depth, respectively;
z is the transverse distance measured from shore; and
B is the river width.

The dispersion coefficient is related to σ^2 by:

$$\frac{d\sigma^2}{dx} = \frac{2E_z}{\bar{U}}$$

where $\bar{U}$ is the average velocity; and
x is the distance below source.

DESCRIPTION OF STUDY AREA

A system of sampling ranges across the river has been used to monitor several water quality indicators since 1967. The study reach considered here is comprised of five ranges (Figure 1). The range near the headwaters of the river was included to define the background level. The remaining four ranges are downstream from industrial activities in Sarnia.

This report is based on hydraulic characteristics, chloride loadings and chloride levels in the river as measured in 1974.

In 1974, chloride inputs from Dow Chemical of Canada Limited accounted for 93 percent of the total chloride loadings to the river from Canadian sources (unpublished Ministry data). While the discharge took place through eight outfalls, the input from the 4th Street Outfall accounted for 90 percent of the total loading from the company. It has therefore, been assumed that the increase in chloride levels above background result from a point source located at the above outfall. This outfall is taken as the reference point for dispersion prediction in the river.

The average velocity over the study reach at a flow of $6800 m^3/s$ (240,000 cfs) was estimated to be 0.83 m/s (2.7 ft/sec) and the average depth was 10m(33 ft.). Local velocities along the sampling ranges were obtained from the U.S. Corps of Engineers and the Water Survey of Canada (Figure 2). These velocities were verified by using a Bendix Q9 current meter provided by the Water Modelling Section.

The average shear velocity (U_*) was found to be 0.042 m/s (0.14 ft/sec) using Manning's equation:

$$U_* = \frac{n\sqrt{g}}{H^{1/6}} \bar{U} \text{ in metric units}$$

where n is the Manning's roughness coefficient = 0.0235 (Quinn and Hagman 1977),

g is the acceleration due to gravity = 9.8 m/sec^2; and

H is the average depth of water flow.

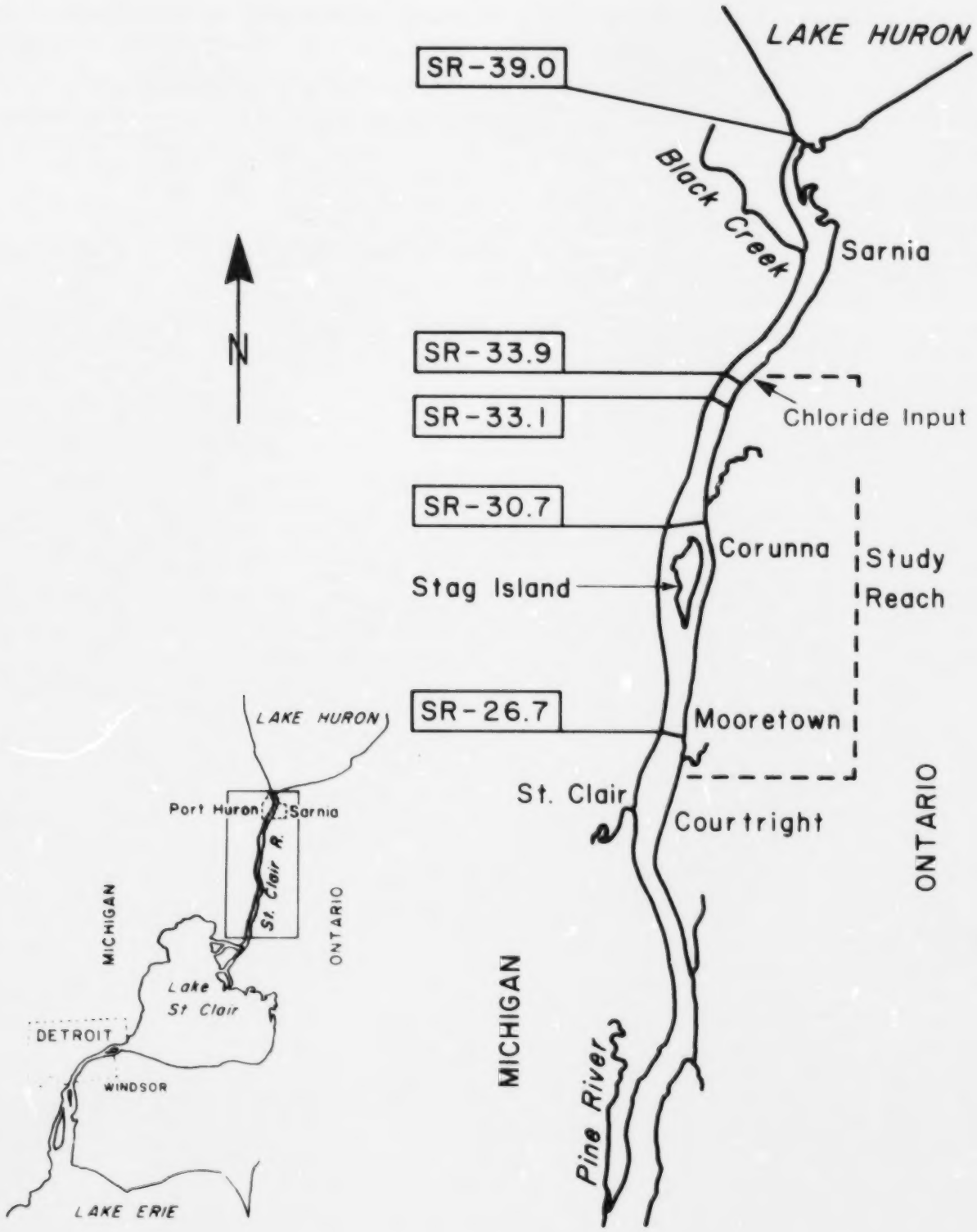
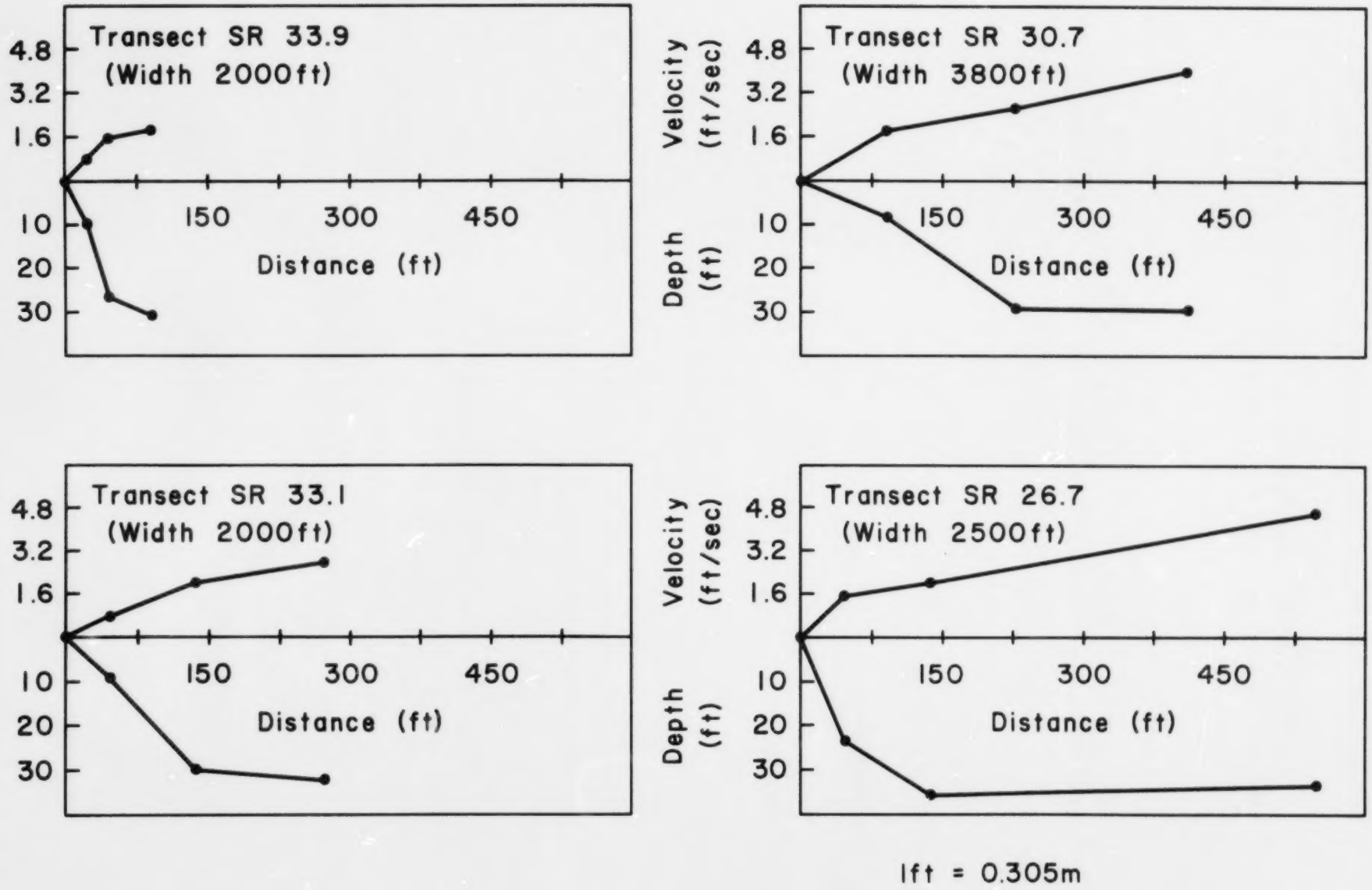


FIGURE 1 ST. CLAIR RIVER DISPERSION STUDY



1ft = 0.305m

FIGURE 2 ST. CLAIR RIVER HYDRAULIC CHARACTERISTICS

ESTIMATION OF THE LATERAL DISPERSION COEFFICIENT (E_z)

The 1974 chloride concentrations measured at distances from the Canadian shore of the river are shown in Table 1.

TABLE 1

Transect	Dist. below Source (m)	Lateral Dist. from Shore (m)	Net Chloride Conc.* ± Standard Deviation (mg/l)	n
SR-33.9	300	8	66 ± 22	4
		15	41 ± 12	4
		30	1 ± 0	4
SR-33.1	1600	15	49 ± 12	4
		46	20 ± 2	4
		91	1 ± 0	4
SR-30.7	5400	30	15 ± 0.3	6
		76	7 ± 0.1	6
		137	1 ± 0	6
SR-26.7	12000	15	9 ± 0.5	6
		46	6 ± 0.1	6
		183	1 ± 0	6

*Background Concentration = 7 mg/l

Of particular interest is the relatively short lateral distances required for the chloride concentrations to approach the background level. This indicates that the plume is confined to the shore.

The transverse distribution of a conservative substance was found by Hinze (1959), Sayre and Chang (1968) and others to be close to Gaussian:

$$c_z = c_s \exp(-z^2/2\sigma^2)$$

$$\text{or} \quad \ell n\, c_z = \ell n\, c_s - z^2/2\sigma^2$$

where c_s, c_z are concentration at shore (s) and at lateral distance (z) from shore; both at longitudinal distance (x) below the source; and

σ^2 is the variance of Gaussian concentration distribution.

The data presented in Table 1 seem to indicate that the Gaussian equation can be used to represent the transverse chloride distribution in the St. Clair River.

Based on the above equation, the transverse distribution was estimated for each transect along with the associated variances (Figure 3). These variances, however, do not include the effect of depth and velocity variation which, as mentioned earlier, may influence the prediction of the lateral mixing coefficient.

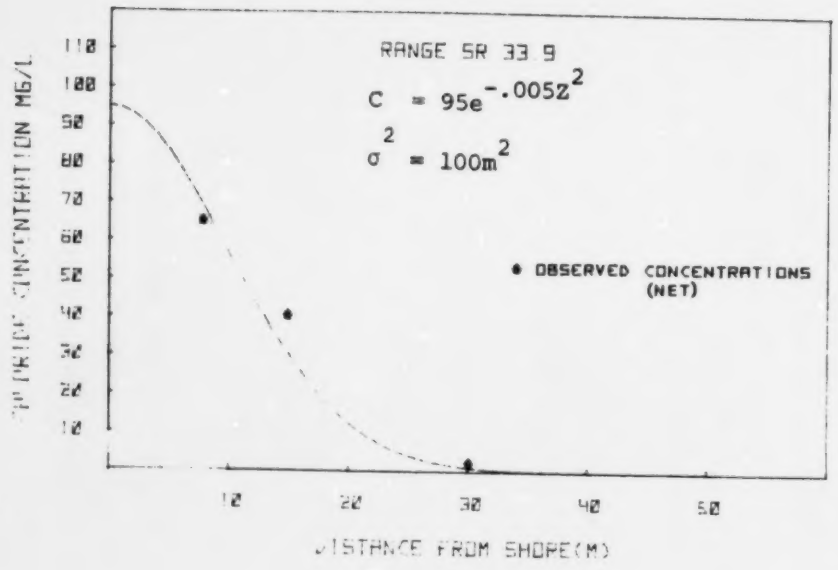
The estimated flux at each transect is shown in Figure 4. The low flux value at 300 m from the source may be attributed to a non-uniform vertical distribution of concentrations coupled with fluctuations in the discharge rate from the source. This phenomenon was experienced by Holley and Abraham (1973). Farther downstream, the flux approached the prevalent discharge rate.

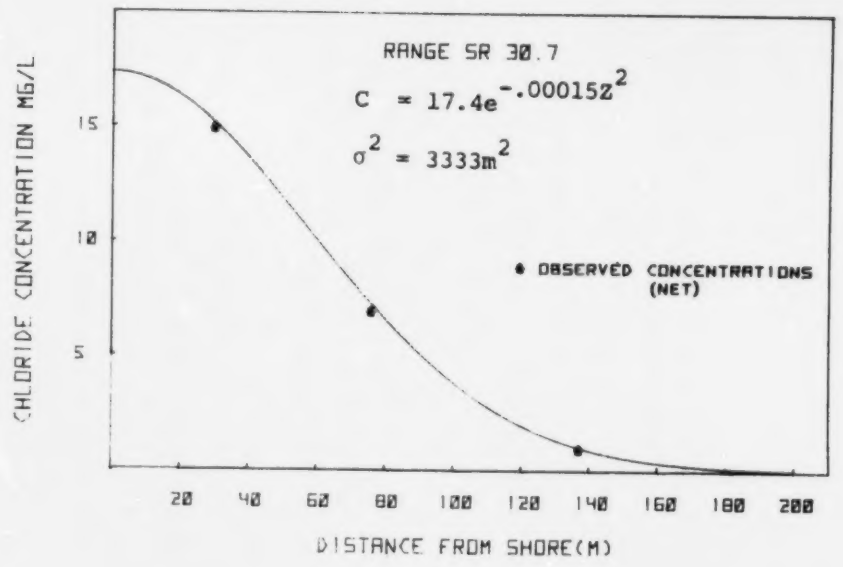
Estimates of variance of the flux concentration distribution were made based on the moment method and are summarized in Table 2.

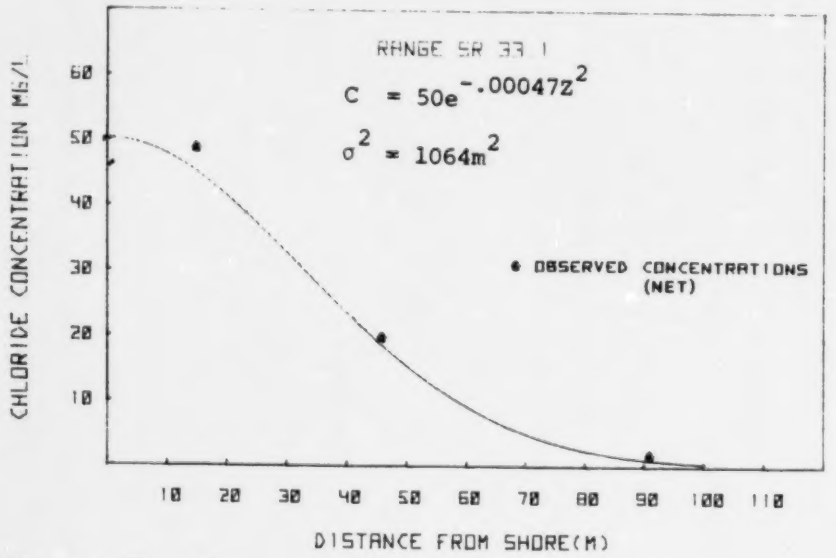
TABLE 2

Range	Variance (m^2)
SR-33.9	240
SR-33.1	2300
SR-30.7	6300
SR-26.7	9700

Variances (σ^2) of the chloride distribution flux were found to be greater than those obtained from the concentration distribution at transects near the source with both variances being similar at large distances from the source.







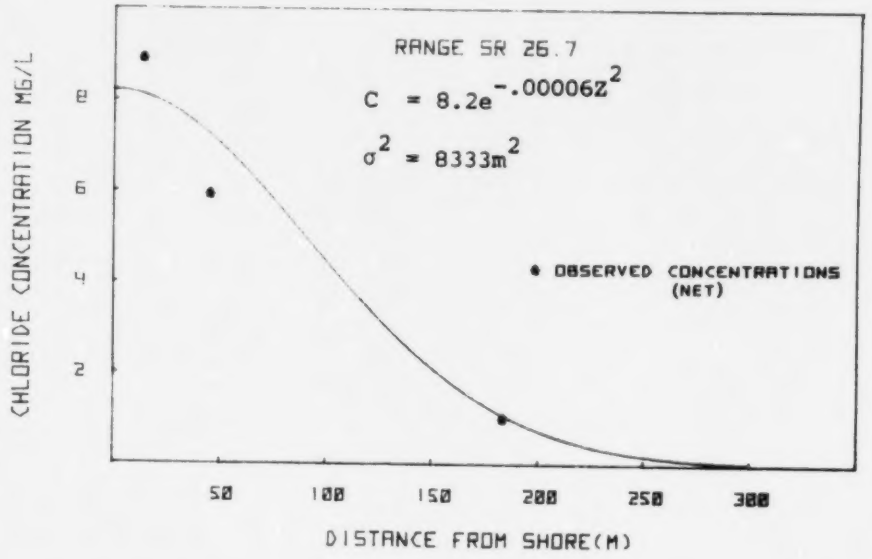


FIGURE 3 CHLORIDE CONCENTRATION PROFILES

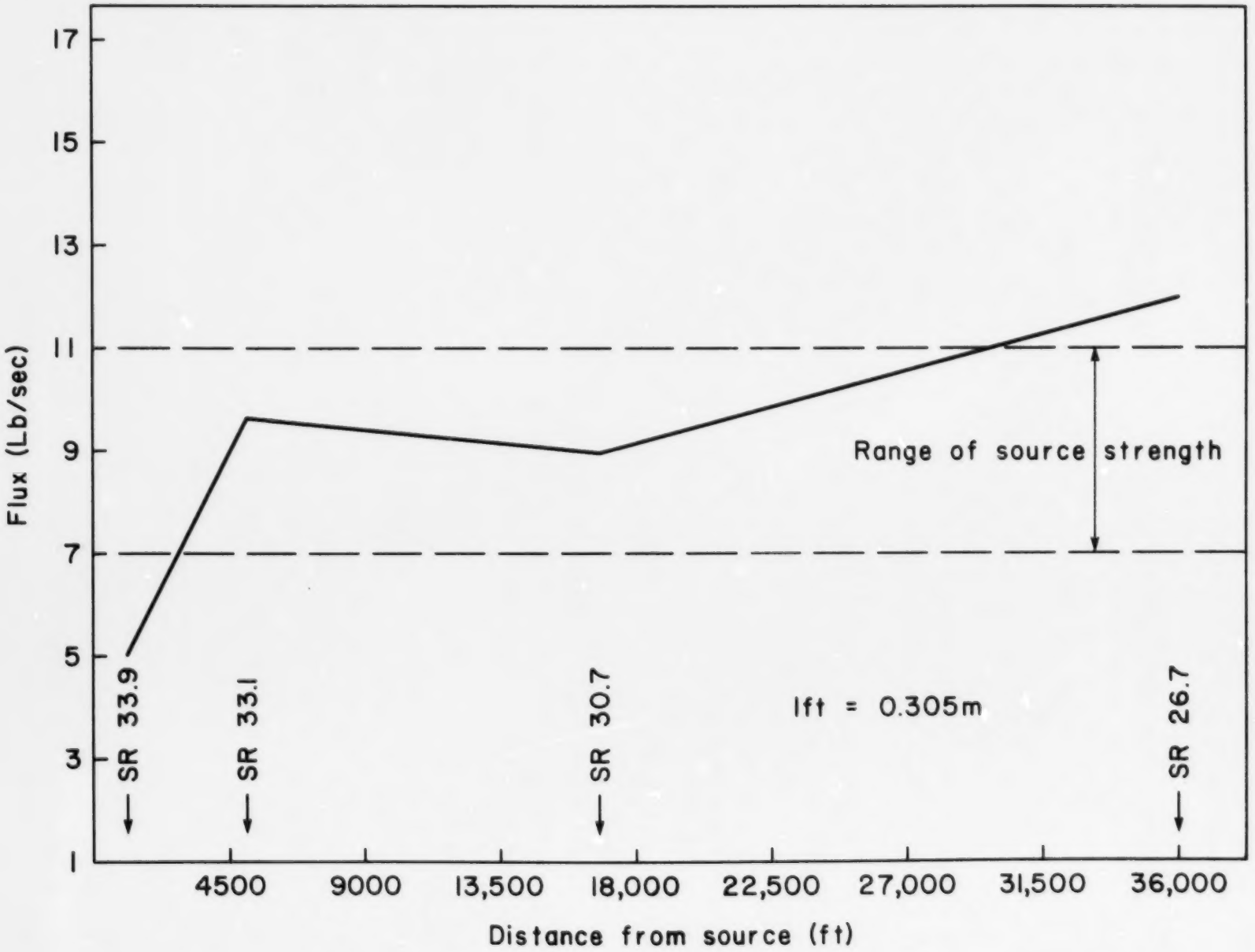


FIGURE 4 CHLORIDE FLUX

The growth of variance with longitudinal distance (x) from the source was found to be non-linear. The least square trend line for the growth of variance is shown in Figure 5.

The corresponding empirical equation for the trend line was similar to that found by Orlob (1959):

$$\sigma^2 = mx^n$$

where n is the slope = 1.0182
m is the intercept = 0.898

By differentiating the above equation and knowing that:

$$E_z = \frac{1}{2} \bar{U} \frac{d\sigma^2}{dx}$$

we found that:

$$E_z = 0.449 \bar{U} x^{.0182}$$

Based on an average velocity during the study period of 0.83 m/s, estimates for the lateral dispersion coefficients at each range were determined as follows:

TABLE 3

Range	Lateral Dispersion Coefficients (E_z)
	m^2/sec
SR-33.9	0.39
SR-33.1	0.41
SR-30.7	0.41
SR-26.7	0.43

The non-dimensional dispersion coefficient ($E_z/U_\star H$) was found to range from 0.93 to 1.0 based on average values of shear velocity (.042 m/s) and depth (10m).

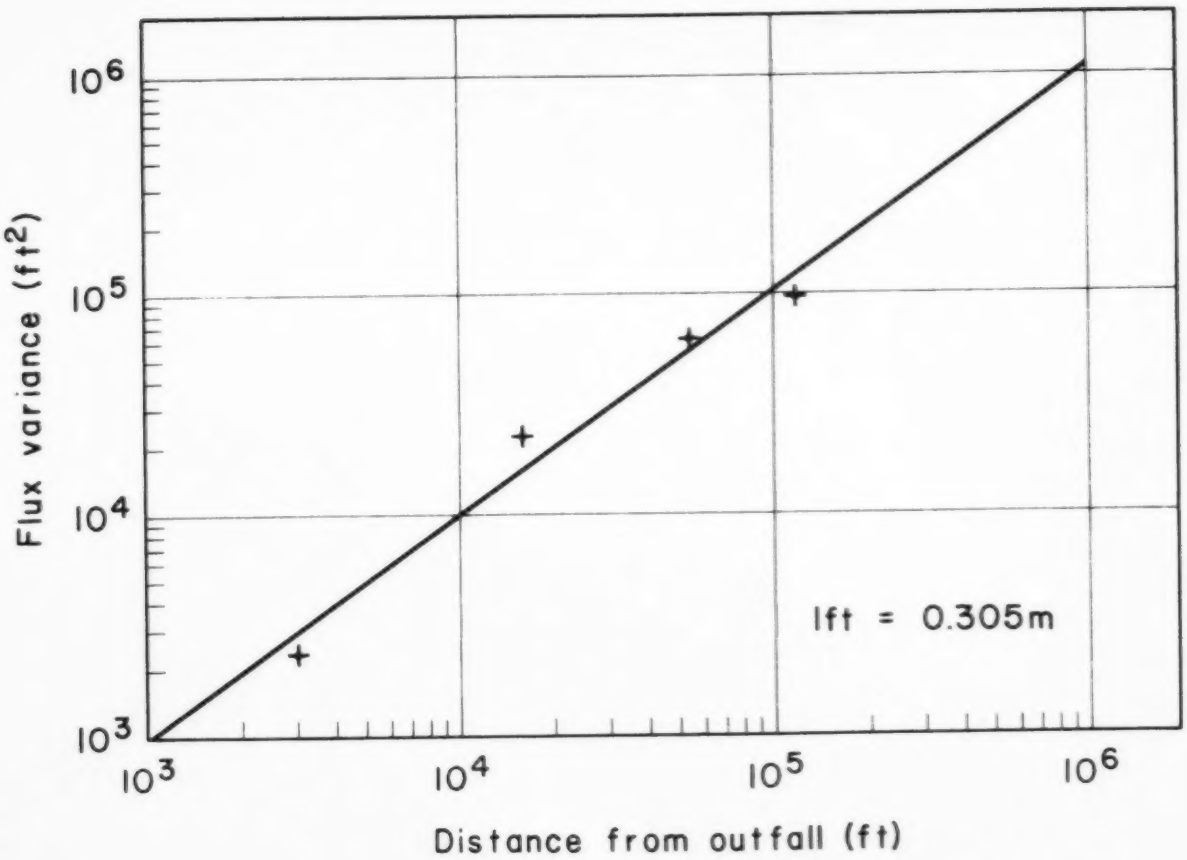


FIGURE 5 GROWTH OF MEAN VARIANCE

During low flow conditions in the river as observed in recent years (1977-1978), the non-dimensional dispersion coefficient remained almost the same ($\simeq 0.96$), however; the extent of the plume downstream from the source was larger than that observed earlier.

The high non-dimensional dispersion coefficient observed in the St. Clair River, as in other large streams, is a clear deviation from the conventional value of 0.23 which is commonly used.

APPLICATION TO DISPERSION PREDICTION

Conservative Pollutants

Having developed an estimate for the lateral dispersion coefficient, we now are able to predict the fate of shore-based waste discharges using a reduced form of the mass conservation equation (Verboom 1974):

$$E_z \frac{\partial^2 c}{\partial z^2} + \frac{Q}{h} = \bar{U} \frac{\partial c}{\partial x}$$

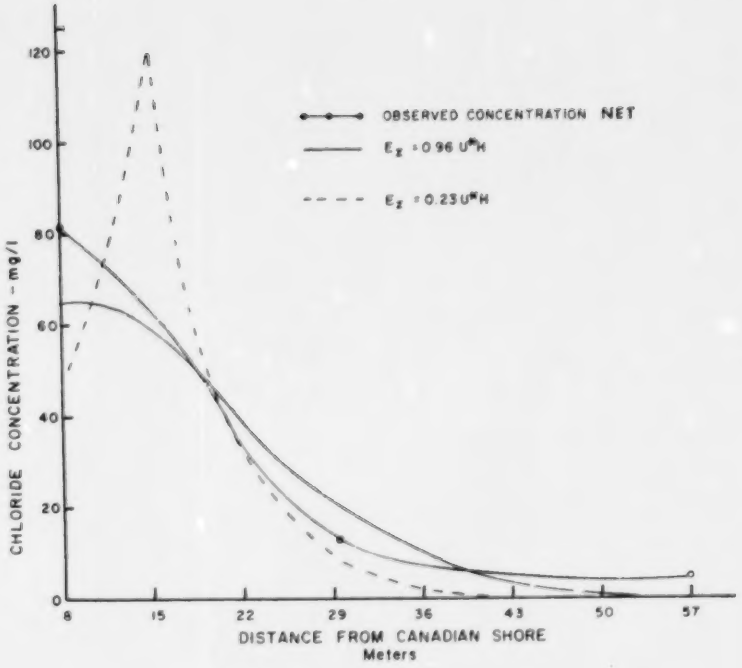
It is assumed in this equation, that the material is being released continuously at a constant rate Q and that the diffusive transport in the flow direction is negligible in comparison with the advective transport.

In a parallel study, Akhtar and Mathur (1974) used the above equation in a two-dimensional model to describe the dispersion process in the river. They used the classical value of 0.23 for the non-dimensional dispersion coefficient in the development of their predictions. When they reran the model using our estimate of 0.96 they found that the transverse chloride distribution predicted by the model agreed well with the observed (Figure 6).

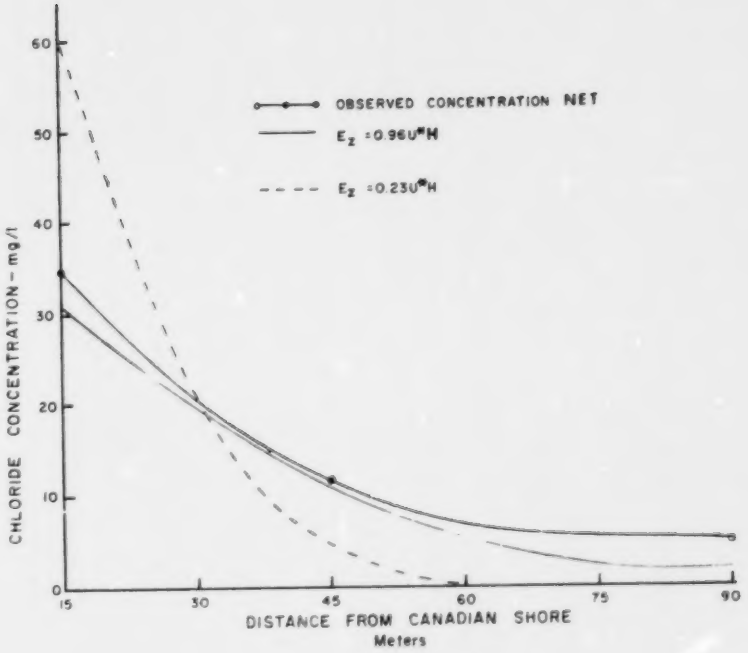
We have simplified their approach through a solution of the above equation for a point source which employs the method of images as described by Sayre and Chang (1968) and documented by Holley et al (1972):

$$c_r = \frac{Q}{h\sqrt{\pi E_z u x}} \sum_{n=-\infty}^{n=+\infty} \exp\left[-\frac{u(z-2nB)^2}{4E_z x}\right]$$

where c_r is the relative concentration.
($c_r = c/c_e$; c_e is the effluent concentration)



RANGE 33.9



RANGE 33.1

FIGURE 6 PREDICTED VS OBSERVED CHLORIDE CONCENTRATIONS AFTER AKHTAR & MATHUR

Three values (0, +1, -1) for n (number of images) were found to be sufficient to obtain stable concentrations based on a procedure developed by Gowda (1977).

The relative concentrations at longitudinal distance x from source and transverse distance z from shore are depicted in Figure 7 for the discharge rate of 3 m^3/s which prevailed during the study period.

Verification of the point source model was made using chloride concentrations measured in 1976 when the source strength of the 4th St. outfall was 2.6 kg/s (discharge rate of $3m^3/s$ and initial concentration of 860 mg/l). Figure 8 shows the close agreement with the observed in both the longitudinal and transverse directions.

The model should also be applicable for other discharge rates provided they are small in comparison to the river flow, a requirement that is routinely met in in the St. Clair River and the other connecting channels.

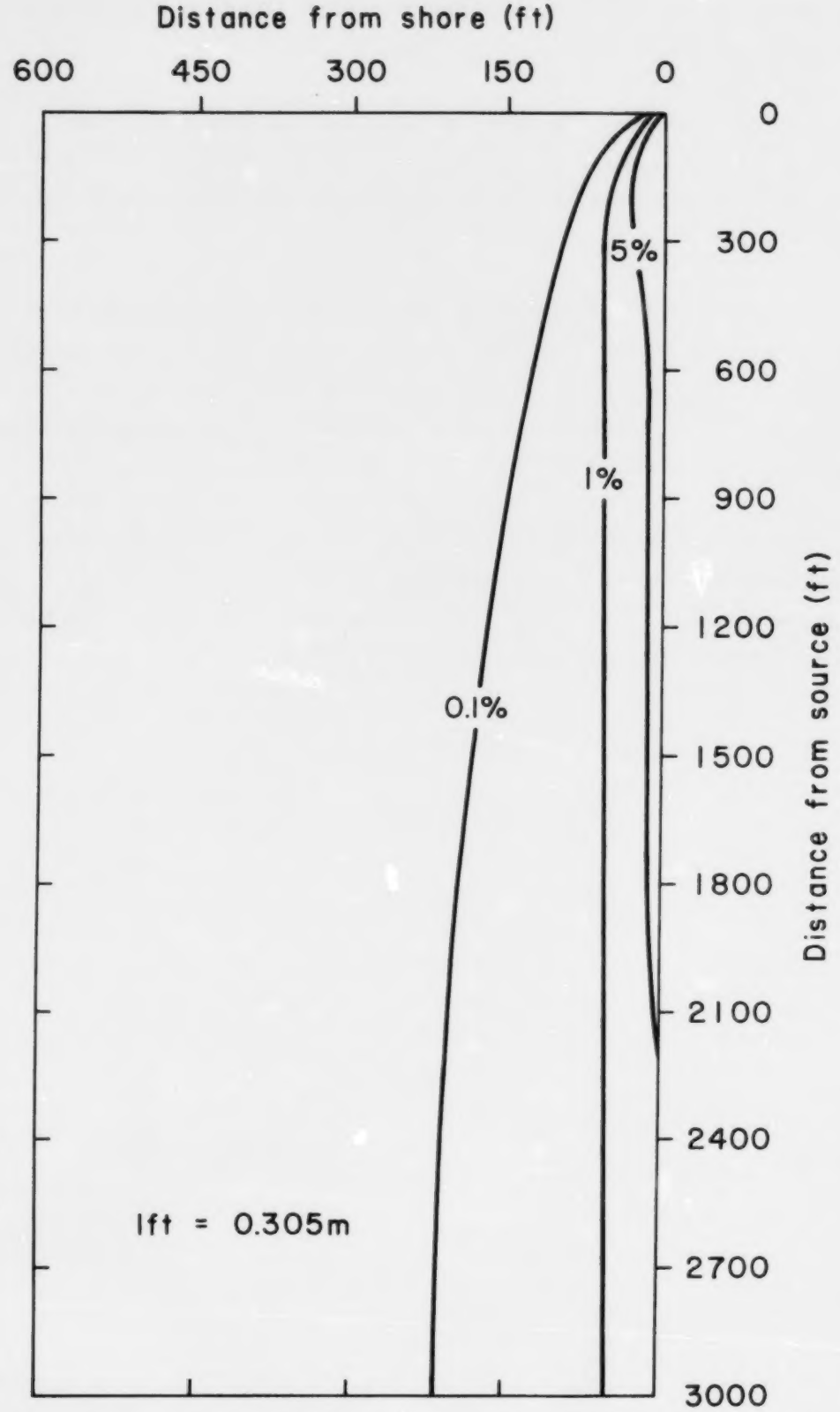


FIGURE 7 RELATIVE CONCENTRATION DISTRIBUTION (c/c_e x 100)
for $Q = 3m^3/s$

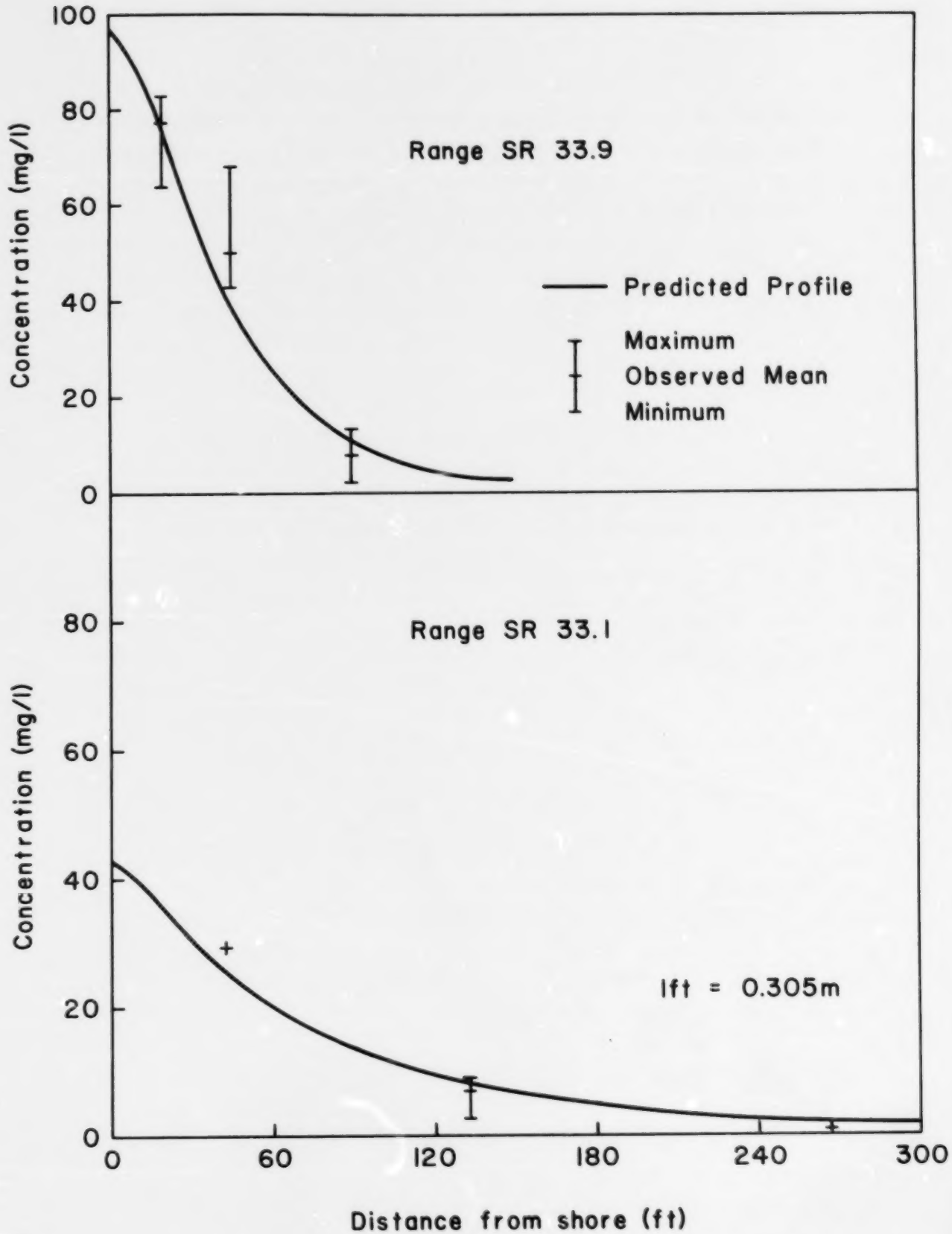


FIGURE 8 MODEL VERIFICATION - PREDICTED VS OBSERVED CHLORIDE CONCENTRATIONS

Non-Conservative Pollutants

The model can also be used to predict the fate of non-conservative substances by applying appropriate decay functions which account for a variety of removal or conversion processes such as volatilization, sorption and chemical and biochemical reaction. These processes are in turn governed by other factors such as temperature, alkalinity, dissolved oxygen content, vapour pressure solubility, and the presence of other pollutants. Decay functions therefore are highly specific to the particular substance and to the receiving water characteristics existing at a particular location and point in time.

As a first step toward refining the model to handle non-conservative pollutants the Ministry is presently funding a survey of the literature on removal and conversion rates for several of the more common inorganic and organic contaminants.

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APPENDIX A

Non-Dimensional Dispersion Coefficient

E_z/U_*H	Channel Characteristics	Source	Reference
0.16	Laboratory flume: 1.2 ft. width, 0.04 ft. depth, U_*=0.052 ft/sec, U=0.71 ft/sec	Elder 1959	2
0.17	Laboratory flume: 1.2 ft. width, 0.48 ft. depth, U_*=0.13 ft/sec, U=0.77 ft/sec	Sayre/Chang 1968	5
0.22	Laboratory flume: 8 ft. width, 050 ft. depth	Glover 1964	4
0.24	ATRISCO Feeder Canal: 60 ft. width, 2.2 ft. depth, U_*=0.21 ft/sec, U=2.12 ft/sec.	Fischer 1966	7
0.60	Missouri River (near Nebraska): 740 ft. width, 9 ft. depth, U_*=0.24 ft/sec, U=5.74 ft/sec.	Yotsukura et al 1970	6
0.72	Columbia River (near Richland): 1000 ft. width, 12 ft. depth, U_*=0.29 ft/sec, U=4.43 ft/sec.	Glover 1964	4